η' production in proton-proton collisions far from the threshold

Antoni Szczurek

Institute of Nuclear Physics PAN, PL-31-342 Cracow, Poland
University of Rzeszów, PL-35-959 Rzeszów, Poland

Abstract. I discuss exclusive production of the η' meson in the $pp \to p\eta' p$ reaction far from the threshold. The contribution of diffractive component as well as that for $\gamma^*\gamma^* \to \eta'$ fusion are calculated. In the first case the formalism of unintegrated gluon distribution functions (UGDF) is used. The distributions in the Feynman x_F (or rapidity), transferred four-momenta squared between initial and final protons (t_1, t_2) and azimuthal angle difference between outgoing protons (Φ) are calculated. The deviations from the $\sin^2(\Phi)$ dependence predicted by one-step vector-vector-pseudoscalar coupling are quantified and discussed. The results are compared with the results of the WA102 collaboration at CERN. Most of the models of UGDF from the literature give too small cross section as compared to the WA102 data and predict angular distribution in relative azimuthal angle strongly asymmetric with respect to $\pi/2$ in disagreement with the WA102 data. This points to a different mechanism at the WA102 energy. Predictions for RHIC, Tevatron and LHC are given.

Keywords: exclusive production of η', QCD diffraction, photon-photon fusion, differential distributions
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INTRODUCTION

The search for Higgs boson is the primary task for the LHC collider being now constructed at CERN. Although the predicted cross section is not small it may not be easy to discover Higgs in inclusive reaction due to large background in each of the final channel considered. An alternative way is to search for Higgs in exclusive or semi-exclusive reactions with large rapidity gaps. Although the cross section is not large, the ratio of the signal to more conventional background seems promising. Kaidalov, Khoze, Martin and Ryskin proposed to calculate diffractive double elastic (both protons survive the collision) production of Higgs boson in terms of UGDFs [1]. It is not clear at present how reliable such calculations are. Here I shall present application of this formalism to the production of η' meson.

Recently the exclusive production of η' meson in proton-proton collisions was intensively studied slightly above its production threshold at the COSY ring at KFA Jülich [2] and at Saclay [3]. Here the dominant production mechanism is exchange of several mesons (so-called meson exchange currents) and reaction via S_{11} resonance [4].

In the present note we study the same exclusive channel but at much larger energies ($W > 10$ GeV). Here diffractive mechanism is expected to be the dominant process. In Ref.[8] the Regge-inspired pomeron-pomeron fusion was considered as the dominant mechanism of the η' production.

There is a long standing debate about the nature of the pomeron. The approximate

$\sin^2(\Phi)$ (Φ is the azimuthal angle between outgoing protons) dependence observed experimentally [5] was interpreted in Ref.[6] as due to (vector pomeron)-(vector pomeron)-(pseudoscalar meson) coupling. To our knowledge no QCD-inspired calculation for diffractive production of pseudoscalar mesons exists in the literature.

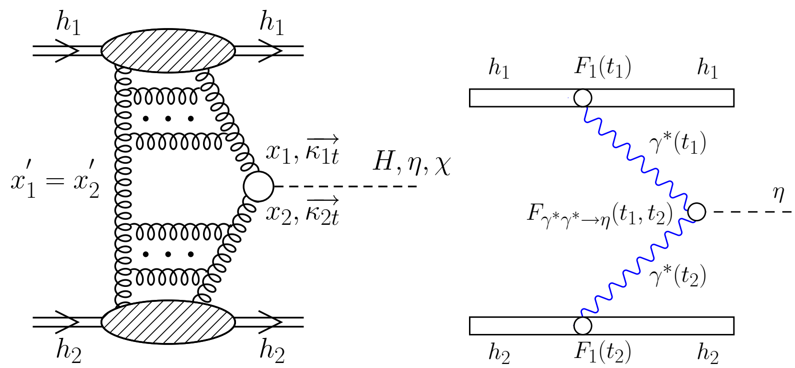

FIGURE 1. The sketch of the bare QCD diffractive mechanism (left panel) and photon-photon fusion mechanism (right channel).

In the left panel of Fig.1 I show the QCD mechanism of diffractive double-elastic production of η' meson. I shall show that approximate ($\sim \sin^2(\Phi)$) dependence is violated in the QCD-inspired model with gluon exchanges within the formalism of unintegrated gluon distribution functions (UGDF). For completeness, the photon-photon fusion mechanism shown in the right panel is included too.

FORMALISM

Following the formalism for the diffractive double-elastic production of the Higgs boson developed by Kaidalov, Khoze, Martin and Ryskin [1, 9] (KKMR) we write the bare QCD amplitude for the process $pp \to p\eta' p$ sketched in Fig.1 as

$$\mathscr{M}^{g^*g^*\to\eta'}_{pp\to p\eta' p} = i\pi^2 \int d^2k_{0,t} V(k_1,k_2,P_M) \frac{f^{off}_{g,1}(x_1,x_1',k^2_{0,t},k^2_{1,t},t_1)\, f^{off}_{g,2}(x_2,x_2',k^2_{0,t},k^2_{2,t},t_2)}{k^2_{0,t}\, k^2_{1,t}\, k^2_{2,t}} . \quad (1)$$

The bare amplitude above is subjected to absorption corrections which depend on collision energy. The vertex function $V(k_1,k_2,P_M)$ in the expression (1) describes the coupling of two virtual gluons to the pseudoscalar meson. The details concerning the function $V(k_1,k_2,P_M)$ can be found in [7].

The objects $f^{off}_{g,1}(x_1,x_1',k^2_{0,t},k^2_{1,t},t_1)$ and $f^{off}_{g,2}(x_2,x_2',k^2_{0,t},k^2_{2,t},t_2)$ appearing in formula (1) are skewed (or off-diagonal) unintegrated gluon distributions. They are non-diagonal both in x and k_t^2 space. Usual off-diagonal gluon distributions are non-diagonal only in x. In the limit $x_{1,2} \to x'_{1,2}$, $k^2_{0,t} \to k^2_{1/2,t}$ and $t_{1,2} \to 0$ they become usual UGDFs. In the general case we do not know off-diagonal UGDFs very well. It seems reasonable, at least in the first approximation, to take

$$f^{off}_{g,1}(x_1,x_1',k^2_{0,t},k^2_{1,t},t_1) \;=\; \sqrt{f_g^{(1)}(x_1',k^2_{0,t}) \cdot f_g^{(1)}(x_1,k^2_{1,t})} \cdot F_1(t_1)\,, \quad (2)$$

$$f_{g,2}^{off}(x_2,x_2',k_{0,t}^2,k_{2,t}^2,t_2) \quad = \quad \sqrt{f_g^{(2)}(x_2',k_{0,t}^2)\cdot f_g^{(2)}(x_2,k_{2,t}^2)}\cdot F_1(t_2)\,, \tag{3}$$

where $F_1(t_1)$ and $F_1(t_2)$ are usual Dirac isoscalar nucleon form factors and t_1 and t_2 are total four-momentum transfers in the first and second proton line, respectively. The above prescription is a bit arbitrary. It provides, however, an interpolation between different x and k_t values.

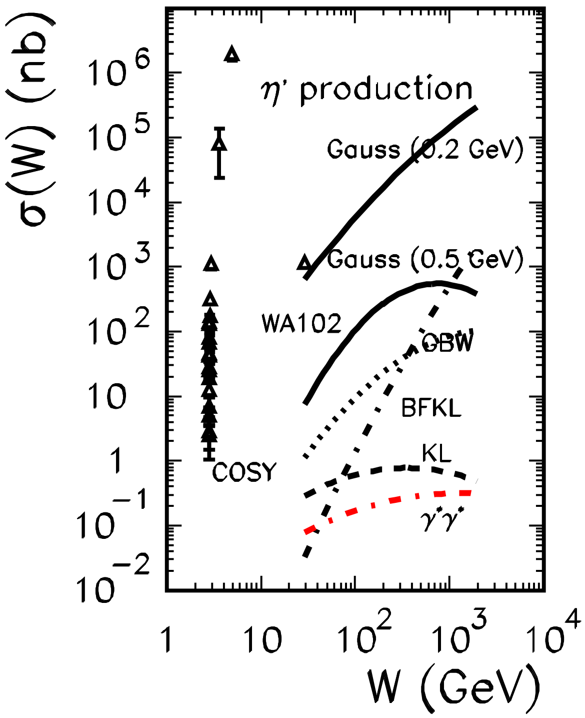

FIGURE 2. σ_{tot} as a function of center of mass energy for different UGDFs. The $\gamma^*\gamma^*$ fusion contribution is shown by the dash-dotted (red) line. The world experimental data are shown for reference.

Neglecting spin-flipping contributions the average matrix element squared for the $p(\gamma^*)p(\gamma^*) \to pp\eta'$ process can be written as [7]

$$\overline{|\mathscr{M}_{pp\to p\eta' p}^{\gamma^*\gamma^*\to\eta'}|^2} \approx 4s^2e^8\frac{F_1^2(t_1)}{t_1^2}\frac{F_1^2(t_2)}{t_2^2}|F_{\gamma^*\gamma^*\to\eta'}(k_1^2,k_2^2)|^2\,|\mathbf{k}_{1,t}|^2|\mathbf{k}_{2,t}|^2\sin^2(\Phi)\,. \tag{4}$$

RESULTS

In Fig. 2 I show energy dependence of the total (integrated over kinematical variables) cross section for the exclusive reaction $pp \to p\eta' p$ for different UGDFs [10]. Quite different results are obtained for different UGDFs. This demonstrates huge sensitivity to the choice of UGDF. The cross section with the Kharzeev-Levin type distribution

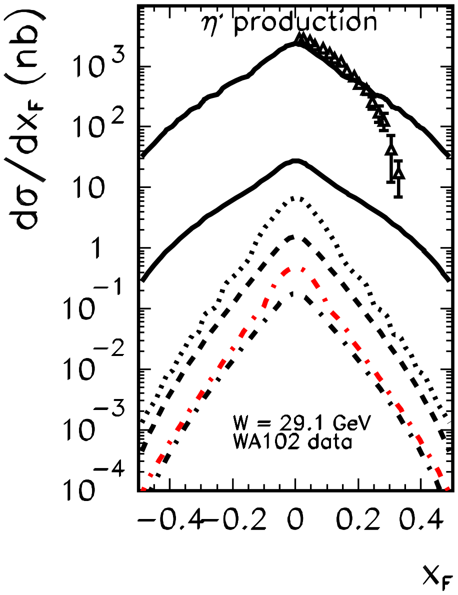

FIGURE 3. $d\sigma/dx_F$ as a function of Feynman x_F for W = 29.1 GeV and for different UGDFs. The $\gamma^*\gamma^*$ fusion contribution is shown by the dash-dotted (red) line (second from the bottom). The experimental data of the WA102 collaboration [5] are shown for comparison.

(based on the idea of gluon saturation) gives the cross section which is small and almost idependent of beam energy. In contrast, the BFKL distribution leads to strong energy dependence. The sensitivity to the transverse momenta of initial gluons can be seen by comparison of the two solid lines calculated with the Gaussian UGDF with different smearing parameter σ_0 = 0.2 and 0.5 GeV. The contribution of the $\gamma^*\gamma^*$ fusion mechanism (red dash-dotted line) is fairly small and only slowly energy dependent. While the QED contribution can be reliably calculated, the QCD contribution cannot be at present fully controlled.

In Fig. 3 I show the distribution of η' mesons in Feynman-x_F obtained with several models of UGDF (for details see [10]). For comparison also the contribution of the $\gamma^*\gamma^*$ fusion mechanism is shown. The contribution of the last mechanism is much smaller than the contribution of the diffractive QCD mechanism.

In Fig. 4 I present distribution in t_1 and t_2 (identical) of the diffractive production and of the $\gamma^*\gamma^*$ mechanism (red dash-dotted curve). The distribution for the $\gamma^*\gamma^*$ fusion is much steeper than that for the diffractive production.

In Fig. 5 I show the distribution of the cross section as a function of the relative angle between the outgoing protons. In the first approximation it reminds $\sin^2(\Phi)$. A more detailed inspection shows, however, that the distribution is somewhat skewed with respect to $\sin^2(\Phi)$ dependence.

In Fig. 6 I present two-dimensional maps $t_1 \times t_2$ of the cross section for the QCD mechanism (KL UGDF) and the QED mechanism (Dirac terms only) for the Tevatron

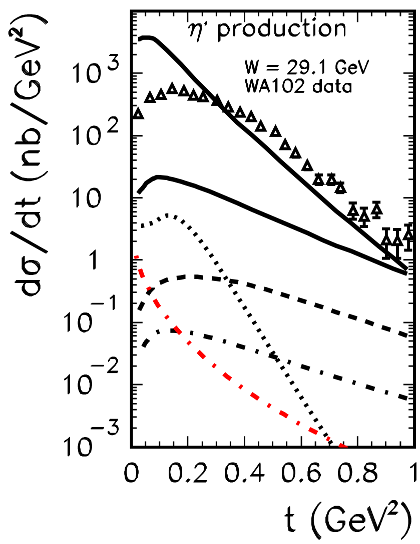

FIGURE 4. $d\sigma/dt_{1/2}$ as a function of Feynman $t_{1/2}$ for W = 29.1 GeV and for different UGDFs. The $\gamma^*\gamma^*$ fusion contribution is shown by the dash-dotted (red) steeply falling down line. The experimental data of the WA102 collaboration [5] are shown for comparison.

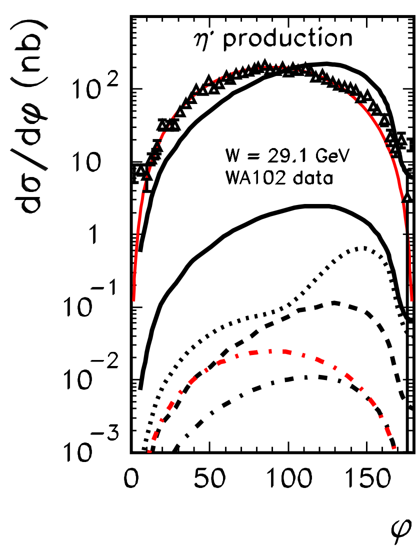

FIGURE 5. $d\sigma/d\Phi$ as a function of Φ for W = 29.1 GeV and for different UGDFs. The $\gamma^*\gamma^*$ fusion contribution is shown by the dash-dotted (red) symmetric around 90^o line. The experimental data of the WA102 collaboration [5] are shown for comparison.

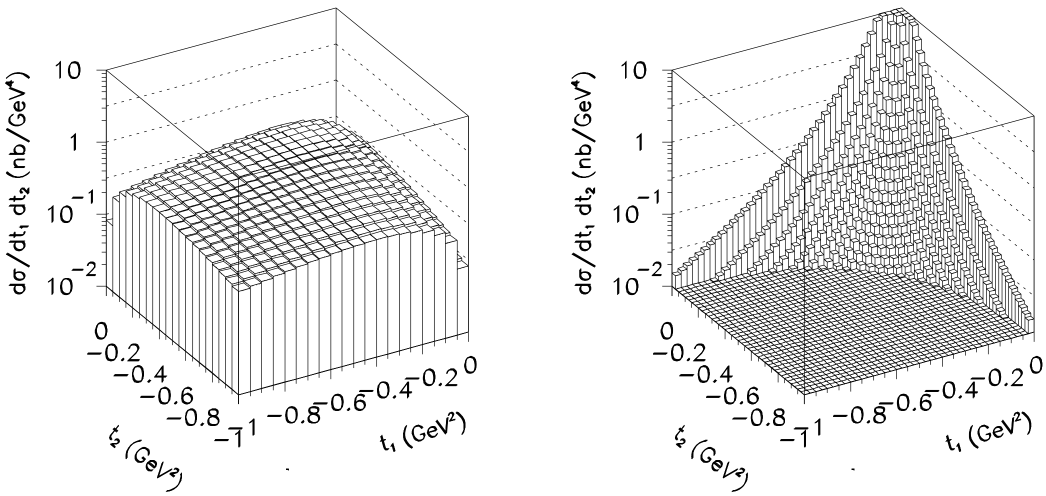

FIGURE 6. Two-dimensional distribution in $t_1 \times t_2$ for the diffractive QCD mechanism (left panel), calculated with the KL UGDF, and the $\gamma^*\gamma^*$ fusion (right panel) at the Tevatron energy W = 1960 GeV.

TABLE 1. Comparison of the cross section (in nb) for η' and η_c production at Tevatron (W = 1960 GeV) for different UGDFs. The integration is over -4 $< y <$ 4 and -1 GeV $< t_{1,2} < 0$. No absorption corrections were included.

UGDF	η'	η_c
KL	0.4858(+0)	0.7392(+0)
GBW	0.1034(+3)	0.2039(+3)
BFKL	0.2188(+4)	0.1618(+4)
Gauss (0.2)	0.2964(+6)	0.3519(+8)
Gauss (0.5)	0.3793(+3)	0.4417(+6)
$\gamma^*\gamma^*$	0.3095(+0)	0.4493(+0)

energy W = 1960 GeV. If $|t_1|, |t_2| > 0.5$ GeV^2 the QED mechanism is clearly negligible. However, at $|t_1|, |t_2| < 0.2$ GeV^2 the QED mechanism may become equally important or even dominant. The details depend, however, on UGDFs.

In Table 1 I have collected cross sections (in nb) for η' and η_c mesons for W = 1960 GeV integrated over broad range of kinematical variables specified in the table caption. The cross sections for η_c are very similar to corresponding cross sections for η' production and in some cases even bigger.

CONCLUSIONS

I have shown that it is very difficult to describe the only exsisting high-energy (W $\sim$ 30 GeV) data measured by the WA102 collaboration [5] in terms of the unintegrated gluon distributions. First of all, rather large cross section has been measured experimentally. Using prescription (3) and on-diagonal UGDFs from the literature we get much smaller cross sections than the measured one. Secondly, the calculated dependence on the azimuthal angle between the outgoing protons is highly distorted from the $\sin^2\Phi$ distribution, whereas the measured one is almost a perfect $\sin^2\Phi$ [7]. This signals that a rather different mechanism plays the dominant role at this energy. Exchange of subleading reggeons is a plausible mechanism.

The diffractive QCD mechanism and the photon-photon fusion lead to quite different pattern in the (t_1,t_2) space. Measuring such two-dimensional distributions at Tevatron and/or LHC would certainly help in disentangling the reaction mechanism.

Finally we have presented results for exclusive double elastic η_c production. Similar cross sections as for η' production were obtained. Also in this case the results depend strongly on the choice of UGDF.

Measurements of the exclusive production of η' and η_c at Tevatron or LHC would help to limit or even pin down the UGDFs in the nonperturbative region of small gluon transverse momenta where these objects cannot be obtained as a solution of any perturbative evolution equation, but must be rather modelled.

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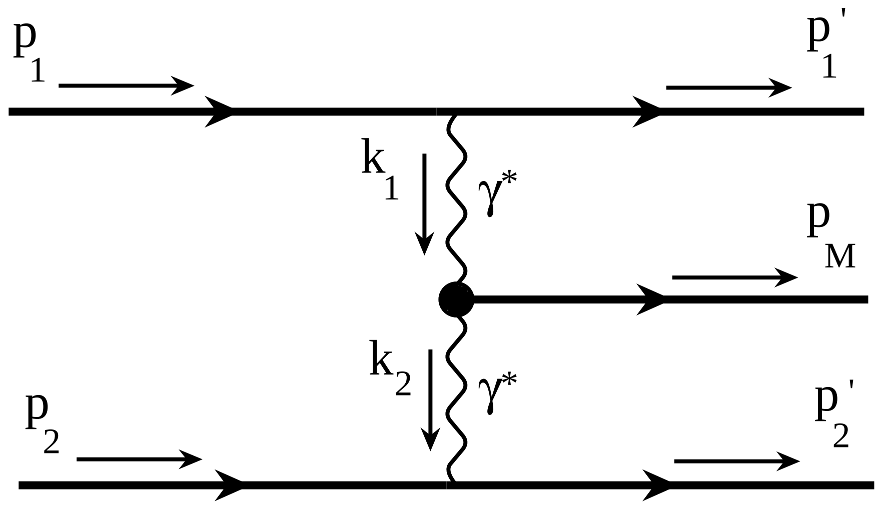
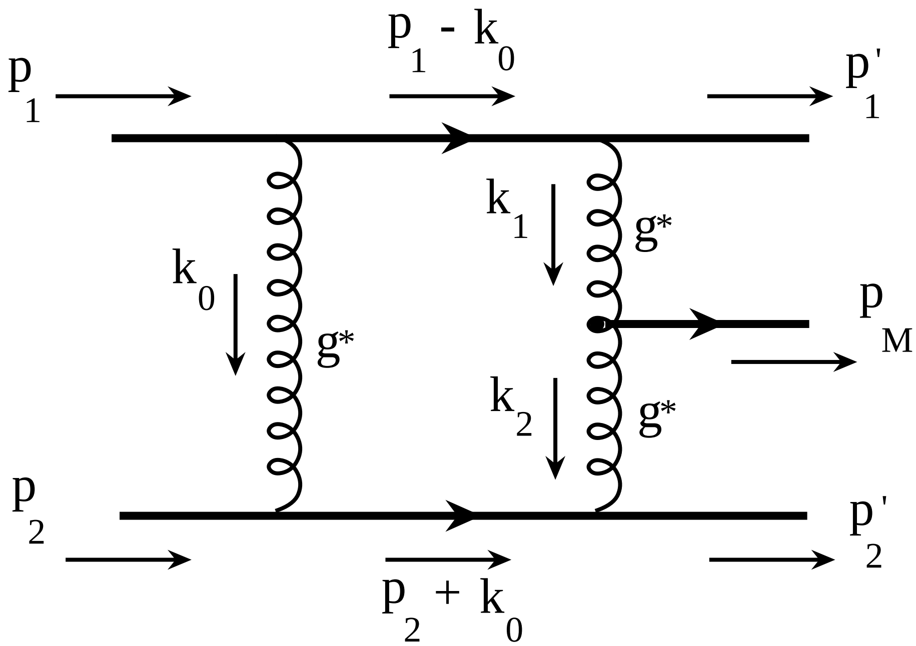
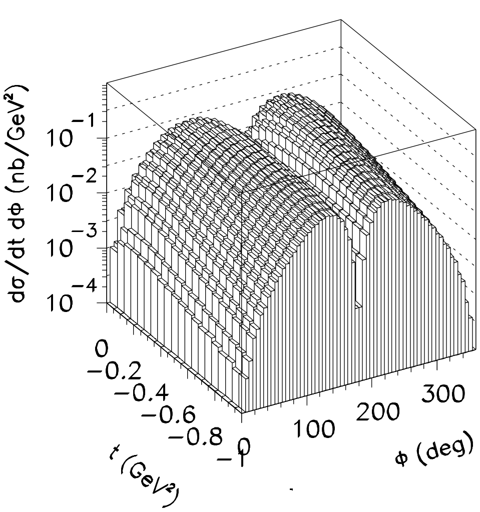


p1
p1'
k1
γ*
pM
k2
γ*
p2
p2'



p1
p1 - k0
p'1
k1
g*
k0
g*
pM
k2
g*
p2
p'2
p2 + k0



dσ/dt dΦ (nb/GeV²)
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
−0.2
−0.4
−0.6
−0.8
−1
t (GeV²)
0
100
200
300
ϕ (deg)